New results With the opto-electronic oscillators (OEO)

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ABSTRACT

A new class of oscillators based on photonic devices is presented. These opto-electronic oscillators (OEO's) generate microwave oscillation by converting continuous energy from a light source using a feedback circuit which includes a delay element, an electro-optic switch, and a photodetector. Different configurations of OEO's are presented, each of which may be applied to a particular application requiring ultra-high performance, or low cost and small size.

1. INTRODUCTION

Oscillators are ubiquitous in a variety of scientific, technological, and commercial applications. in communication systems, all receivers and transmitters process signals generated by, or compared to, reference frequencies produced by reference. oscillators.

in conventional oscillators, electrically generated frequencies are used in conjunction with high Q resonators to produce reference signals with high spectral purity and/or stability. Since the Q of these types of resonators typically degrade with increased frequency, high performance reference signals at frequency of a few to tens of GHz are obtained by multiplying the lower frequency of a reference oscillator, at a cost of generating multiplicative noise. For optical and photonic systems, in yet an additional step, the electrical signals are impinged on an optical carrier, further aggravating the noise and the complexity of the systems.

Recently we introduced a novel oscillator based on photonic components which directly generates spectrally pure and stable references at 1-100 GHz region of the spectrum as intensity modulations of an optical carrier.[1] The first versions of this type of oscillator demonstrated unprecedented spectral purity in a room temperature device and a potential for high stability.[2,3] Since that time, we have devised various techniques to operate these oscillators without electrical amplifiers or filters to further improve their noise performance. In this paper we will review the basis of the operation of these oscillators, and show new results on 'the operation of OEO's without If amplifiers or narrow-band filters. We also examine the ultimate potential of the OEO as a high stability LO for the new class of atomic frequency standards, such as the trapped ion standard, and the cesium fountain.

2. CHARACTERISTICS OF THE OEO

The OEO is a device that converts continuous energy from a light source to stable, and spectrally pure oscillations. The first version of the OEO consisted of a pump laser and a feedback circuit including an intensity modulator, an optical fiber (May line, a photodetector, an amplifier, and a filter, as shown in Fig. 1.

This oscillator represented a particular version of the OEO, which in general can be made from any light source together with any device that can be configured in a closed loop to modulate the intensity or phase of the optical carrier. 'The fiber delay line which plays the role of the conventional high Q resonator for storing energy determines the spectral quality of the signal produced. The version shown in Fig. 1, however, is readily amenable to analysis to derive the expected performance of the oscillator theoretically. We have used a model[3] by setting the small signal gain of the feedback loop consisting of the E/O modulator, the photodetector, and the RF amplifier to unity.

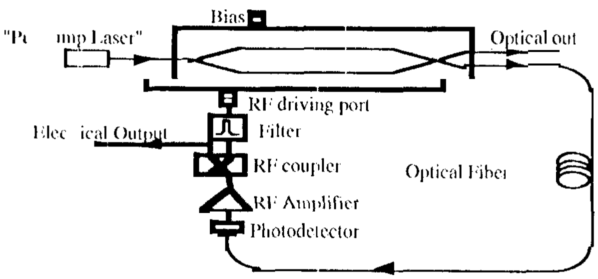

Fig. 1 **Generic** configuration of the OEO.

The signal $V_{out}(t)$ at the output port of the amplifier corresponding to an input signal $V_{in}(t)$ at the driving port of the E/O modulator can be expressed as:

$$V_{out}(t) = V_{ph}\{1 - \eta \sin \pi[V_{in}(t)/V_\pi + V_B/V_\pi]\} \quad (1)$$

where α is the fractional insertion loss of the modulator, V_B is its bias voltage, V_π is its half-wave voltage, P_o is the input optical power, ρ is the responsivity of the detector, R is the load impedance of the detector, GA is the amplifier's voltage gain, $I_{ph} \equiv \alpha P_o \rho/2$ is the detected photocurrent, $V_{ph} \equiv I_{ph} R G_A$ is the photon generated voltage at the output of the amplifier, and η determines the extinction ratio of the modulator by $(1+\eta)/(1-\eta)$. Based on this model, we showed that the threshold condition for the oscillation may be obtained as:

$$V_{ph} = V_\pi / \pi , \quad (2)$$

assuming $\eta = 1$ and $V_B = 0$ or V_π.

As a next step, Eq. 1 may be linearized through the use of a narrow bandwidth filter to block all harmonic components of the signal. The result of this procedure allows the application of the superposition principle and regenerative feedback approach to derive the spectral power density of the oscillation:

$$S_{RF}(f') = \frac{\delta}{(\delta/2\tau)^2 + (2\pi)^2(\tau f')^2} \quad (3)$$

for $2\pi f' \tau << 1$

where f' is the frequency offset from the oscillation frequency f_{osc} and δ is the noise to signal ratio of the OEO and is defined as:

$$\delta = \rho_N G_A^2 / P_{osc} =$$

$$[4 k_B T(NF) + 2eI_{ph}R + N_{RIN} I_{ph}^2 R] G_A^2 / P_{osc} \quad ,(4)$$

where ρ_N is the total noise density input to the oscillator and is the sum of the thermal noise $\rho_{thermal} = 4k_B T(NF)$, the shot noise $\rho_{shot} = 2eI_{ph}R$, and the laser's relative intensity noise (RIN) $\rho_{RIN} = N_{RIN} I_{ph}^2 R$ densities. In Eq. (4), k_B is the Boltzman constant, T is the ambient temperature, NF is the noise factor of the RF amplifier, e is the electron charge, I_{ph} is the photocurrent across the load resistor of the photodetector, and N_{RIN} is the RIN noise of the pump laser.

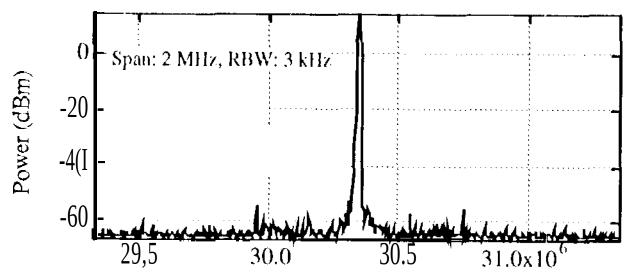

Fig. 2. OEO spectrum without an amplifier.

It is clear from Eq. 3 that the noise of the oscillator is influenced by the amplifier noise. Yet the requirement for self-sustained oscillation given by Eq. 2 implies that to sustain oscillations in the loop (i.e. $G_A = $) only the condition $I_{ph}R \geq V_\pi/\pi$ has to be satisfied. Thus it is possible to obtain oscillations with the OEO without an rf amplifier and its associated noise. This prediction is verified experimentally with an oscillator operating without an amplifier. Figure 2 represents the spectrum of the signal of such an OEO with a 1 km delay at a frequency of about 30 Mhz.

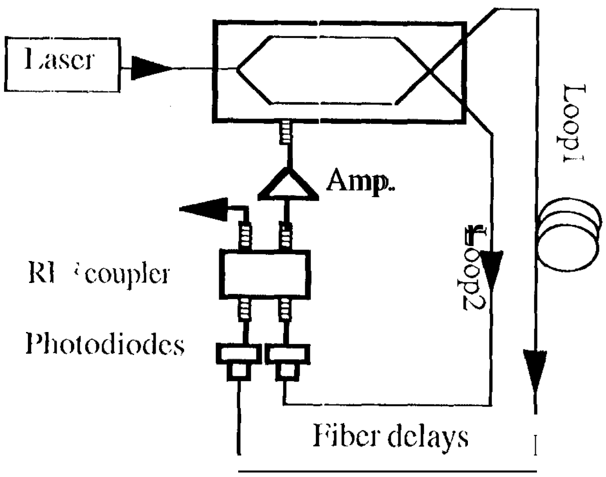

Fig. 3. The Dual Loop OEO

With the elimination of the amplifier, all other components, except for the filter, are photonic. The filter is required to obtain a single mode operation of the OEO which is inherently a multi-mode device. The long delay produced by the fiber to improve the mist performance as prescribed by Eq. 3 above, produces close mode spacing and thus necessitate the use of a narrowband rf filter.

We have recently demonstrated the operation of the OEO with a wide bandwidth rf filter. This was achieved by utilizing a short optical delay line (fiber) in a second feedback loop, as shown in Fig. 3.

in this configuration, the open loop gain of each of the two loops is individually less than unity, but their sum is larger than one. The OEO's oscillation frequency is determined by both loops since the frequencies in each loop must add up in phase for self sustained oscillations. It can be easily shown that the shorter loop determines the mode spacing, which because of the small delay, is large, while the longer loop results in low phase noise. Thus a wideband rf filter suffices to produce low noise oscillations in this dual loop OEO.

3. STABILITY CONSIDERATIONS

While the high spectral purity of the OEO has a number of important applications, the realization of a highly stable oscillator based on this spectral purity is of great significance to the new, ultra-stable, class of atomic frequency standards. In the linear trapped ion standard (LITS), for example, the potential stability of $2 \times 10^{-14}/\tau^{-1/2}$ is not realizable without a flywheel oscillator, or an LO, capable of the same stability for intervals up to about 30 s long, corresponding to the operation cycle of the LITS. Similar LO requirements also exist for the cesium fountain standards.

The stability of the OEO is primarily determined by the stability of the long fiber loop. This is because the electrical and photonic components Of the OEO may be chosen to produce minimal phase variations in the time intervals of interest. The optical fiber, by contrast, sets the limit for the minimum variations of the phase, and the corresponding variation in the frequency achievable with the OEO. A complete analysis of the ultimate achievable stability of the OEO requires the analysis of all the parameters that change the phase, including stimulated Raman, and Brouillon noise in the fiber, and the fundamental thermal fluctuations of the fiber length at any fixed temperature. These parameters are nevertheless quite small compared to the phase delay produced in the fiber due to variations of the ambient temperature. We thus limit ourselves to the consideration of the thermal stability achievable in the fiber delay loop.

Since the fiber with the smallest thermal coefficient of delay (TCD) yields the highest long term stability, we perform the following calculation based on the fiber manufactured by the Sumotomo company. This type of fiber has zero coefficient of delay at a fixed temperature, usually chosen to be 20 degrees Celsius. We have previously characterized the phase delay for this fiber and had determined that the residual variations of the phase delay with small deviations from the temperature of zero delay, T_0, is parabolic and may be given as:

$$\phi(T) = a + b(T - T_0)^2 \text{ deg/m} \qquad (5)$$

where a was found from the data to be -0.802. Using this equation, for a signal with 2 GHz frequency the frequency instability corresponding to T_0 = 5 deg, held to 1 m °C, is computed to be 1.57×10^{-14}. This value is encouraging, since it is in the range of interest for 1,0 applications. It also corresponds to holding the temperature of the fiber to a one m °C level, which is readily achievable. If the temperature of the fiber is maintained to 0.01 m °C, then another order of magnitude in the stability will be reached.

As mentioned above, careful determination of the ultimate achievable stability at the levels of interest requires accounting for all other sources of noise, including residual instability due the variations of the laser frequency. We are currently engaged in the determination of all sources of noise, and the quantification of their contribution to the achievable frequency stability with the OEO.

4. SUMMARY

The OEO is a novel type of oscillator which has already produced impressive performance. Because of its physical basis, the OEO is particularly useful in applications where the highest spectral purity performance is required at frequencies ranging from a few to many tens of GHz. The theoretical model developed for the performance parameters of the OEO successfully confirms the experimental results. I particular, it was shown both theoretically and experimentally that the OEO may operate without an rf amplifier in its feedback loop. The need for a bandpass filter was also eliminated by the use of a dual loop configuration. According to the model the noise of the OEO is predicted to be limited by the amplitude noise of the laser, and may be reduced to the shot noise level of the photodetector. This prediction will be pursued in future experimental work.

We also showed that the stability of an oscillator based on the OEO may be limited above one second integration times by the thermal stability of the long fiber delay line. For the special fiber with zero coefficient of delay, we showed that stability of better than two parts in 10^{14} may be obtained. Thus the OEO holds the promise of providing a simple and high performance local oscillator for the new class of ultra-stable atomic standards. Further work in our laboratory is planned to realize this important function of the OEO.

5. REFERENCES

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